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# Neuroprostheses

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## 729G43 Project

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This report is about a series of devices naming neuroprostheses, which are mind-controlled artificial extensions that replace missing body parts. A brief history of the development of prostheses will be first introduced, followed by their functioning and the constructions. The purpose as well as the main focus is to find out about how these neuroprosthetics devices are built. The possible issues concerned in building these devices will also be revealed.

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## **Introduction**

Many people in the world living with limb loss as a result of disease and injury. There are two millions amputated patients in just the United States ("Limb Loss Statistics", 2015). Apart from birth defects, the main causes of limb loss are amputations lead by vascular disease such as diabetes, and physical injuries from accidents and warfare. Amputees do not only need to accept that parts of their bodies are missing, but also the consequences that affect their psychological states. Losing limbs affects even the simplest daily activities and some may therefore lost hope in life. Some may have a hard time accepting themselves being incomplete and thus suffer from mental illness like Post traumatic stress disorder. Phantom pain syndrome is also common among amputated patients and it is difficult to be treated. People who have phantom pain experience mild to extreme pain in the area where a limb has been amputated. Fortunately, thanks to human inventions and technological advances, they are given new chances in their lives replacing the loss limbs with artificial ones and they regain the opportunities to live lives as they used to be.

## Terminology

A brief explanation of phrases are presented in alphabetical order as follows.

|                                                          |                                                                                                                                                                                                                                       |
|----------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b><i>Action potential</i></b>                           | Action potentials are caused when different ions cross the neuron membrane.                                                                                                                                                           |
| <b><i>Artificial neural network (ANN)</i></b>            | Artificial neural networks (ANNs) are a family of models inspired by biological neural networks (the central nervous systems of animals, in particular the brain)                                                                     |
| <b><i>Brain computer interface (BCI)</i></b>             | Also known as brain machine interface (BMI)                                                                                                                                                                                           |
| <b><i>Central nervous system (CNS)</i></b>               | The complex of nerve tissues that controls the activities of the body. In vertebrates it comprises the brain and spinal cord.                                                                                                         |
| <b><i>Contralateral</i></b>                              | Of or pertaining to the other side. The opposite of ipsilateral (the same side).                                                                                                                                                      |
| <b><i>Electroencephalography (EEG)</i></b>               | An electroencephalogram (EEG) is a test that detects electrical activity in your brain using small, flat metal discs (electrodes) attached to your scalp.                                                                             |
| <b><i>Intracranial electroencephalography (IEEG)</i></b> | A type of electrophysiological monitoring that uses electrodes placed directly on the exposed surface of the brain to record electrical activity from the cerebral cortex.                                                            |
| <b><i>Osseointegration</i></b>                           | Osseointegration refers to a direct structural and functional connection between ordered, living bone and the surface of a load-carrying implant.                                                                                     |
| <b><i>Perceptron</i></b>                                 | It is an algorithm for supervised learning of binary classifiers: functions that can decide whether an input belongs to one class or another.                                                                                         |
| <b><i>Phantom pain syndrome</i></b>                      | Phantom limb syndrome is the perception of sensations, including pain, in a limb that has been amputated. People with this condition experience feelings in the limb as if it were still attached to their body.                      |
| <b><i>Post traumatic stress disorder (PTSD)</i></b>      | It is a mental health condition that's triggered by a terrifying event — either experiencing it or witnessing it. Symptoms may include flashbacks, nightmares and severe anxiety, as well as uncontrollable thoughts about the event. |
| <b><i>Posterior parietal cortex</i></b>                  | It is the portion of parietal neocortex posterior to the primary somatosensory cortex plays an important role in producing planned movements.                                                                                         |

***Primary motor cortex***

The primary motor cortex, or M1, is one of the principal brain areas involved in motor function. M1 is located in the frontal lobe of the brain, along a bump called the precentral gyrus (figure 1a). The role of the primary motor cortex is to generate neural impulses that control the execution of movement.

***Real-time processing***

Real time processing is usually found in systems that use computer control. This processing method is used when it is essential that the input request is dealt with quickly enough so as to be able to control an output properly. This is called the 'latency'.

***Somatosensory cortex***

The somatosensory system is the part of the sensory system concerned with the conscious perception of touch, pressure, pain, temperature, position, movement, and vibration, which arise from the muscles, joints, skin, and fascia.

***Telemetry***

Telemetry is an automated communications process by which measurements are made and other data collected at remote or inaccessible points and transmitted to receiving equipment for monitoring. The word is derived from Greek roots: tele = remote, and metron = measure.

***Threshold***

The magnitude or intensity that must be exceeded for a certain reaction, phenomenon, result, or condition to occur or be manifested.

## **Development of artificial limbs**

Artificial limbs are first used in about 300 BC ("Brief History of Prostheses", 2015). They are made by iron and wood in the form of a rod. As a matter of fact, they are not very functional but they at least give a sense of "wholeness" to the wearers. Later on prostheses are made with joints (ankles and wrists), which allow more natural movement and less clumsiness although fine motor skills are still rather difficult to be achieved. Mechanisms and materials of prosthetic devices are further improved. Devices are made from more resilient materials such as plastic and stainless steel. Finer parts such as finger and toes are also included.

The demand for prosthetic limbs boosted drastically after the Second World War. Efforts are put into the manufacture of artificial limbs and thus explain the advancements in areas such as material, computer design methods and surgical techniques (Clements, 2008). The focus started to shift to the controllability of the devices.

Myoelectric prosthetic limbs (Alcaide-Aguirre, Morgenroth & Ferris, 2013), are one of the more advanced devices in this field. The limbs are controlled by the muscles remaining in the residual limb that can still be contracted. Electrodes are placed on the surface of the skin which measure muscle movements and the electrical signals generated by the muscles. There are "gloves" specifically made for these devices in order for it to look as likely as actual skin and flesh.

Finally, it comes to the focus of this report - neuroprosthetics<sup>1</sup> (Andersen, Corneil, Greger, Musallam & Scherberger, 2004). They are considered as technological breakthroughs because after some time of adjusting and rehabilitation, they can be fully controlled by the wearers with their thoughts. Theoretically it is identical to moving an actual limb and one very interesting and mesmerising point about some of these devices is that they can also restore the wearers' physical sensations of the missing limb. More information about the neuroprosthetics will be revealed in the next chapter.

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<sup>1</sup> Also known as intelligent prosthetics and mind-controlled prosthetics.

## **What exactly are neuroprostheses and how do they work?**

### *Artificial limbs that are moved by the mind and provide sense of touch*

Neuroprostheses are artificial limbs that are controlled by thoughts, and some of them even provide the sense of touch to their wearers. They are systems that comprised of different components. Before a person wears this kind of prosthetic limb, brain implants are attached to certain areas of the brain cortices that correspond to the functions of the limb through surgical operation. An implant is made of electrode arrays that transfer electrical signals between the brain and the robotic limb. This forms a brain-computer interface which will be further explained later. The robotic limb is attached to the person's body via a process known as osseointegration (MacDonald, 2014), meaning that the artificial limb is directly inserted to the bone. The use of neuroprostheses give back the wearers the ability to move and to feel. They can be without any help in daily activities or even doing sports that require fine motor movements such as indoor climbing (BEC CREW, 2015). Despite the actual composition of the limbs like skin and muscles, it is functionally as if they are real, inborn, natural limbs.

### *Can anyone wear neuroprostheses?*

So far only amputees are mentioned as target users, however people who are born with missing limb(s) can also wear neuroprosthetic devices. The only constrain for any potential user is that its brain remains intact (Banich & Compton, 2011), meaning that it does not suffer from any brain damage specially in and around areas where the sensors are planted. It is because sensors need to receive signals from the brain in order for the robotic limb to work. If the connection between the brain and the prosthetic system is broken, information cannot be transmitted and the limb will not be moved or felt at all.

### *Mechanisms of neuroprostheses*

First of all it is necessary to understand a little about how the brain is connected to the body. The primary motor cortex is responsible for conscious movements. The signals are sent from the cortex to the spinal cord, then to the muscle cells which cause them to contract and result in movements. However, it does not occur all the time that we think of every step of movements when a task is carried out. We think of the goal rather than the process and this intention of movements is aimed by the posterior parietal cortex. Signals are again sent from the cortex to the muscle cells through the spinal cord. On the other hand, tactile information, such as pressure and temperature, is sent from the nerve endings of a body part to the spinal cord and then to the primary somatosensory cortex (Banich & Compton, 2011).



The mechanisms of neuroprosthetic devices are similar to that of the motor and sensory pathways. Sensors in the brain implant and the robotic limbs replace neurons in the brain cortex and a biological limb. In other words, brain signals are transmitted from the motor cortex through the implant directly to the receivers in the limb to stimulate movements, while sensory information is sent from the pressure sensors in the limb to the brain implant in the sensory cortex, which allow the wearer to perceive touch sensations (Murphy, 2015).

## **How are these mind-controlled prosthetic limbs built?**

### *Brain-computer interface*

The communication system that connects between the brain and the robotic arm is called a brain-computer interface (BCI) (McFarland D & Wolpaw J, 2002). The implants that are brought up in earlier sections are BCIs, which transfer brain signals to the external prosthetic device. Note that the motor and sensory cortices control movements and perceive sensations on the contralateral side of the body (Banich & Compton, 2011), so BCIs are inserted on the left brain hemisphere of a person with prosthetic device on its right side.

Each electrode array in the BCI records neural activities in the motor cortex through intracranial electroencephalography<sup>2</sup> (iEEG) (Leuthardt, Roland & Ray, 2014). Signal-processing algorithms are employed to convert neuronal firings into the commands to a robotic manipulator in the external device. The manipulator and the BCI are connected by wireless telemetry and once the manipulator receives the commands, motor output will be produced (Nicolelis & Lebedev, 2009). Sensory input perception is similar to the production of movement, only it goes the other way around from the sensors of the robotic device to the brain.

BCIs in neuroprosthetics are independent, endogenous and invasive. The natural motor and sensory pathways (between the brain and the body) is disrupted, and the routes become between the electrode arrays and the robotic device. The BCIs are not dependent to the brain's pathways and therefore are said as independent; Endogeneity is the property of something being influenced within a system. An endogenous BCI is thus based on the patterns of signals within the brain. Instead of the limb being triggered by external stimuli, neuroprosthetics wearers need to learn to produce these patterns in order to match the command in producing movements; This kind of BCIs are invasive as they are implanted onto the brain cortices. Any kinds of foreign objects that are inserted in the person's body are regarded as invasive (Stieglitz et al, 2009).

### *Data collection and recording*

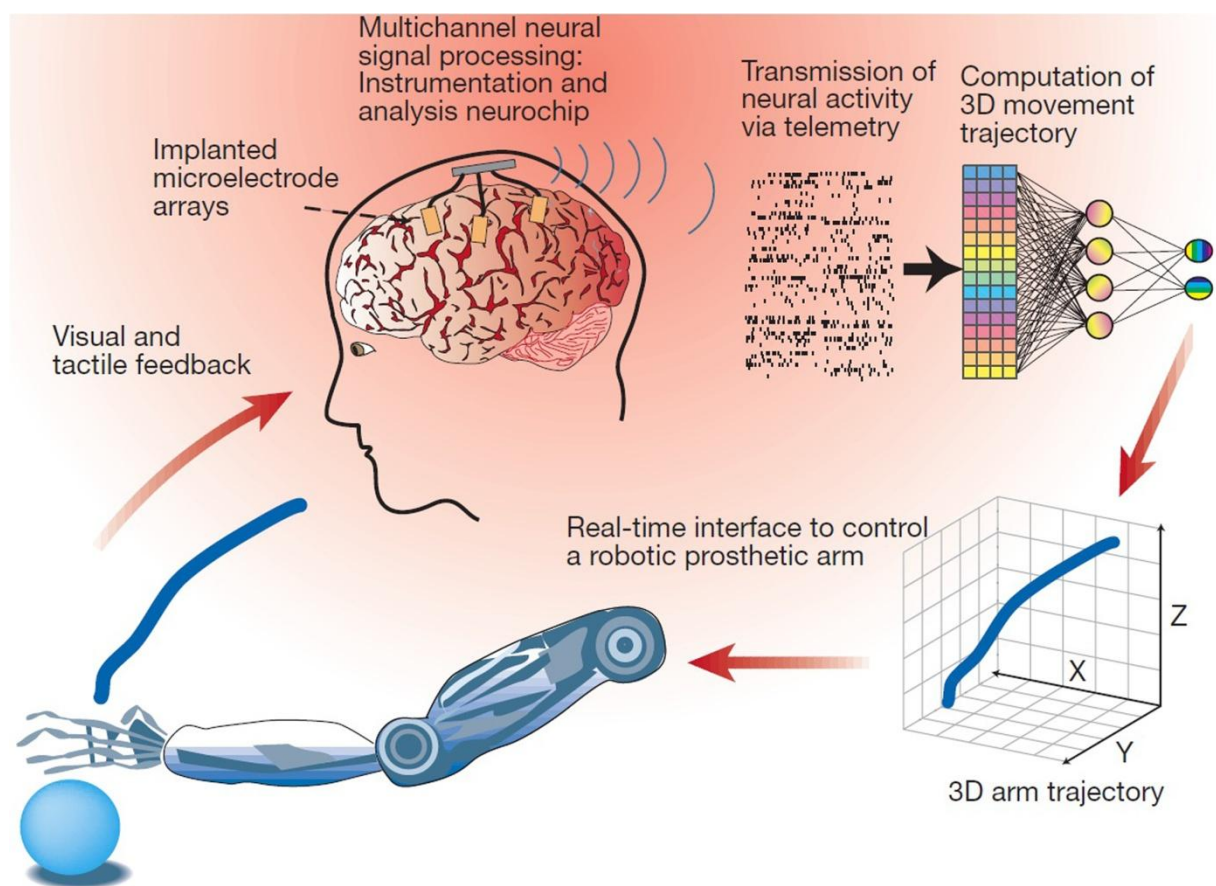
Besides iEEG that has just been mentioned, electroencephalography (EEG) is also used to record brain activities (Leuthardt, Roland & Ray, 2014). The two are very similar, except that the electrodes used in EEG are placed outside the skull instead of inside. This method has

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<sup>2</sup> It is sometimes called electrocorticography (ECoG)

poorer signal-to-noise ratio, but is often used in early clinical trials as it is non-invasive. EEG brain imaging is important as it measures the frequencies, action potentials and locations of the brain signals, these information are needed before any implantation in order to find out where the implants should be placed in the cortices and what kind of signals triggers different movements. Brain activities recorded by EEG are produced when the test subject imagines movements, controls a virtual cursor on a computer screen, or opens and closes a robotic hand (that is of course not attached to the person). As the principles of EEG and iEEG are basically the same, the signals recorded by EEG can be used to "train" the BCI to recognise the patterns of movements, so that same movements can later be produced by the same signals on the surface of the cortex recorded by iEEG.

### *System overview*



**Figure 1. Neuroprosthetic system as a closed loop**

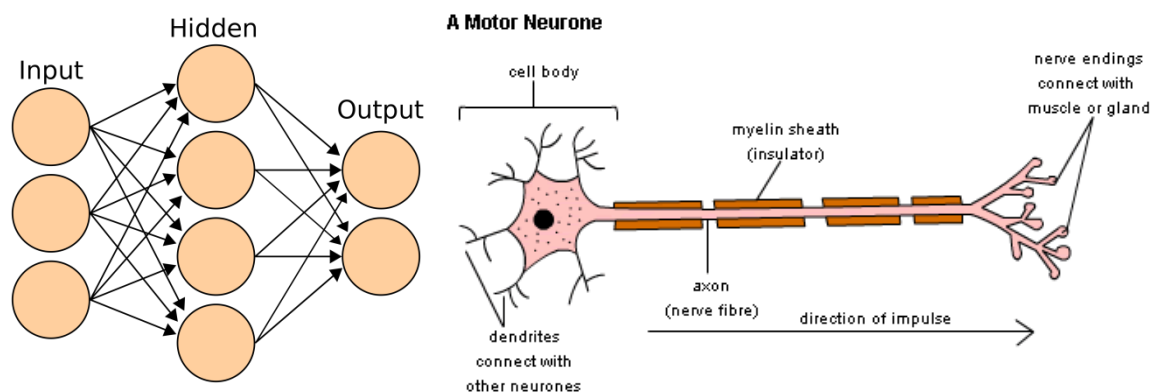
When a thought of movement is initiated and recorded in the BCI, the neural activities are then sent from the telemetric transmitters to the telemetric receivers in robotic device. An advanced pattern recognition algorithm is employed, which translate the neural activities into three-dimensional arm-trajectory signals which determine the device's directions, speeds and

magnitudes of movements before they are performed. This is in fact a closed loop as the wearer perceive visual and tactile feedback signals produced by the movements. (Rothschild, 2010).

### *Real-time processing*

Real-time processing means that the system is performing predictably fast enough (Marsh & Greenwood, 1986). It is important to the neuroprosthetic system because it would be ideal if its motor outputs are identical to natural movements, and jerky motions are not expected and wanted. There are four aspects of real-time performance, naming speed, responsiveness, timeliness and graceful adaptation (Dodhiawala et al, 1989). Speed is how quickly a task is executed, in the case of neuroprostheses the task is the movement of the robotic limb; Responsiveness is the ability of the neuroprosthetic system to generate movements within a given time. The system should recognise the brain signals in the BCI and decide what to do with the input information; Timeliness is the system's ability to react to and meet deadlines. The amount of slack time is related to this aspect; Graceful adaptation is that the system can reset task priorities according to changes in work load or resources availability. The system can choose to execute what is the most appropriate and urgent task in the situation.

### *Artificial Neural Network and perceptron learning*



**Figure 2. An artificial neural network (left) and Figure 3. A biological neuron (right)**

Artificial neural networks (ANN) are algorithms that work in a similar way as the biological neural networks in the central nervous system (Stergiou & Siganos). They are organised in layers which are made up of interconnected nodes. The layers are the input layer with nodes that receive input), the output layer containing nodes that generate output and the hidden layer(s) where nodes communicate with one another within the network. It is the same principle as in biological neurons by which the input nodes act as dendrites, interconnecting nodes act as a neuron cell body and the nerve endings on the axon act as output nodes.

In neuroprosthetic devices, feed-forward ANN is acquired which allows only one way travels from input to output nodes (Ardestani et al, 2014). It is especially used in pattern recognition so that brain signals can be "learnt" to generate designated movements. A multilayer perceptron is a feed-forward ANN model as well as learning algorithms that constructs outputs (Gales, 2015). When the input nodes receive signals from the BCI, the output may be generated, depending on whether the combined signals are strong enough. The decision is made by the perceptrons. If the combined signal inputs are higher than the threshold value in order for the neuron to fire, output will be produced and therefore the prosthetic limb will move.

The multilayer model consists of two layers as in figure 2. The input layer is usually considered as layer zero. The first layer is therefore composed of the hidden nodes and the second layer is composed of the output nodes. The input variables are the activation of neurons recorded by the BCI and the output variables are the "end-point locomotion parameters" (Chang *et al.*, 2009), naming the direction, velocity and strength of movement. According to Hincapie and Kirsch (2009), the goal of optimising an ANN is to achieve a good level of generalisation so that signals that are slightly varied can still be recognised. The ideal network should have the smallest structure that can also provide good prediction results. Small architecture is preferred as the training time required is thus shorter.

#### *Input, hidden and output layer*

The input layer receives input from multiple nodes, while only one output node is responsible for giving out information in that layer. Under certain phase of the operation, the inputs are modified by a weight. The weighted inputs will be accumulated and used to determine its output, depending on the threshold value.

The hidden layer is important for the learning and information processing of the network (Chang *et al.*, 2009). The number of hidden neurons are tested to be at best between 25 and 30 nodes as it gives the most accurate prediction of movement.

Before the ANN model can be applied to the robotic device, it needs to be trained in order to recognise the patterns of the neuronal signals of able-bodied individuals (Chang *et al.*, 2009). This training process is divided into two phases, which are the learning phase and the classification phase (djmw, 2004).

### *Learning phase and classification phase*

Learning phase is when weights are modified. The so called pattern recognition is a supervised learning algorithm, which recognise input pattern and also put them into categories. The modifications of weights are necessary because if the same pattern of inputs is presented, the value of the output node that corresponds with the correct category is slightly higher than it is now, and vice versa. Learning occurs as the recognition gets better every time. Eventually, the pattern-category pairs are remembered and in the ideal world it will be able to achieve generalisation and has learned to classify unknown patterns presented.

The weights of the inputs do not change under the classification phase. Instead, a pattern will be transformed at each layer until it reaches the output. In our case the pattern is transformed twice. During classification, the category with the largest output value is selected.

### *Bayesian Maximum Likelihood Estimation*

Maximum-Likelihood techniques are used and are based on A-Priori measurements, meaning that the technique depends on assumptions of what is known, rather than on observation. The reason is that it is difficult to isolate and record individual neurons. Individual neurons without a precisely defined relationship to a motion parameter makes the predicting performance less ideal. Therefore, it is problematic to define a the parameter space outside of a controlled experimental situation (Ludwig, 2009).

Bayesian maximum likelihood prediction of stimuli marginalize over the distribution of parameters in order to make predictions (Ludwig, 2009). Ludwig assumes that the mean firing rate for a neuron when at rest is 40Hz. The probability of this neuron firing  $n$  times over a time interval  $\Delta t$  while at rest is represented by equation 1:

$$P(n \text{ spikes} | \text{stationary}) = (40\Delta t)^n e^{-(40\Delta t)} / n!$$

If movement is included with the firing rate of 80Hz is recorded, the probability of this neuron firing  $n$  times over a time interval  $\Delta t$  while moving, is represented by equation 2:

$$P(n \text{ spikes} | \text{right}) = (80\Delta t)^n e^{-(80\Delta t)} / n!$$

Given an observed firing rate of 7 spikes over 200 ms, equation 1 becomes:

$$P(7 \text{ spikes over } 200 \text{ ms} | \text{stationary}) = (40 \text{ Hz} * 0.2 \text{ s})^7 \text{ spikes} e^{-(40 \text{ Hz} * 0.2 \text{ s})} / 7 \text{ spikes!}$$

$$= 0.1396$$

Equation 2 becomes:

$$P(7 \text{ spikes over } 200 \text{ ms} | \text{right}) = (80 \text{ Hz} * 0.2 \text{ s})^7 \text{ spikes} e^{-(80 \text{ Hz} * 0.2 \text{ s})} / 7 \text{ spikes!}$$

$$= 0.0060$$

Now according to Bayes' law, the probability of the neuron remaining stationary given an observed firing rate of 7 spikes over 200 ms becomes:

$$P(\text{stationary} | 7 \text{ spikes over } 200 \text{ ms}) = \frac{P(7 \text{ spikes over } 200 \text{ ms} | \text{stationary})}{P(7 \text{ spikes over } 200 \text{ ms} | \text{stationary}) + P(7 \text{ spikes over } 200 \text{ ms} | \text{right})}$$

$$= 0.1396 / (0.1396 + 0.0060) = 0.9588, \text{ or approximately } 96 \text{ percent}$$

Similarly, the probability of motion given an observed firing rate of 7 spikes over 200 ms is:

$$P(\text{right} | 7 \text{ spikes over } 200 \text{ ms}) = \frac{P(7 \text{ spikes over } 200 \text{ ms} | \text{right})}{P(7 \text{ spikes over } 200 \text{ ms} | \text{stationary}) + P(7 \text{ spikes over } 200 \text{ ms} | \text{right})}$$

$$= 0.0060 / (0.1396 + 0.0060) = 0.0412, \text{ or approximately } 4 \text{ percent}$$

Assume the threshold is 95 percent, because 0.9588 is larger than 0.95, the prosthetic device is moved. And as 0.0412 is less than 0.95, the device remains stationary.

This method can also be applied in multiple neurons and multiple stimulus parameters.

Assuming that the previously determined mean firing rate of a group of neurons with respect to a specific stimulus  $s_j$  is defined as the vector  $M_j$ :

$$M_j = \{\mu_{j1}, \mu_{j2}, \dots, \mu_{jn}\}$$

$n$  is the total number of recorded neurons and  $\mu_{ji}$  is the mean firing rate of neuron  $i$  during stimulus  $s_j$ .

Given a vector of observed neuronal responses  $R$  from this group of neurons, where  $r_i$  is the observed firing rate from neuron  $i$  of  $n$  neurons:

$$R = \{r_1, r_2, \dots, r_n\}$$

The probability of an observed response vector  $R$  during the specific stimulus  $s_j$  is:

$$P(R|s_j) = \prod_{i=1}^n (\mu_{ji} \Delta t)^{r_i} e^{-(\mu_{ji} \Delta t)} / r_i!$$

The probability of an observed response vector  $R$  during the specific stimulus  $s_j$  is:

$$S = \{s_1, s_2, \dots, s_n\}$$

Assuming the delivery of all stimuli in set  $S$  are equally probable, the probability of any specific stimuli  $s_j$  based on observed response vector  $R$  can be computed as follows:

$$P(s_j|R) = P(R|s_j) / \sum_{i=1}^n P(R|s_i)$$

This basic Bayesian framework is usually extended to include movement parameters in order to refine spontaneous movement predictions. (Ludwig, 2009)



## **What could be the problems in building them?**

### *Ethical problem*

Can a person still be called a real person if an intelligent system has become a part of it? And is the person controlling its own thought anymore? A lot of attentions are raised by the use of BCI, apart from whether or this kind of system should be used (Olsson, 2014). Because it requires implantation in the brain, animal and human rights are concerned in testing these systems. The procedure takes medical risks and severe consequences might follow if anything goes wrong in the surgery, therefore it is also difficult to find test subjects.

### *Drawback of artificial neural network*

ANN requires rather long period to learn, as it needs a large diversity of training for real operation. Different patterns of signals need to be registered for every movement for the ANN to recognise and learn. The large number of patterns may also mean a large memory burden.

### *Real-time problem*

As the BCI has limitations in memory and speed just like every processor, the performance of the system may not be able to reach optimality. If the prostheses wearer is multitasking, the system might not be able to "translate" lots of distinct patterns in such short period of time. The knowledge base of the system also need to be big enough to recognise all the movement, but yet small enough for the system to avoid information overload and system failure.

## **Conclusion**

This report has covered the mechanisms of neuroprosthetic devices, about how they work and how they are built. Implants made of electrode arrays are inserted onto a person's motor and sensory cortices. The robotic limb that is "plugged" into the person's bone to replace the missing limb. It receives motor signals from the BCI in the motor cortex and sends sensory inputs to BCI to the sensory cortex through telemetry.

These kind of systems are also linked to several theories in artificial intelligence, including brain-computer interface, artificial neural network and perceptron learning. The problems raised by the construction as well as the use of the system are also pointed out.

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